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Author(s)	Noda, Nao-Aki; Otsuka, Hyato; Ando, Makoto; Shinozuka, Takahiro; Guan, Wenhai
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Strain rate concentration and dynamic stress concentration for double-edge-notched specimens subjected to high speed tensile loads

Nao-Aki Noda*, Hayato Ohtsuka, Hongbin Zheng, Yoshikazu Sano, Makoto Ando,

Takahiro Shinozaki, Wenhai Guan

Department of Mechanical Engineering, Kyushu Institute of Technology, 1-1, Sensui-cho,
Tobata, Kitakyushu 804-8550, Japan

*Corresponding author: Tel +81 93 884 3124, Fax +81 93 871 8591,
E-mail noda@mech.kyutech.ac.jp

ABSTRACT

Engineering plastics provide superior performance to ordinary plastics for wide range of the use. For polymer materials, dynamic stress and strain rate may be major factors to be considered when the strength is evaluated. Recently, high speed tensile test is being recognized as a standard testing method to confirm the strength under dynamic loads. In this study, therefore, high speed tensile test is analyzed by the finite element method; then, the maximum dynamic stress and strain rate are discussed with varying the tensile speed and maximum forced displacement. The maximum strain rate increases with increasing the tensile speed u/t but the strain rate concentration factor $K_{\dot{\epsilon}}(t) = \dot{\epsilon}_{yA}(t) / \dot{\epsilon}_{ynom}(t)$ is found to be constant independent of tensile speed, which is defined as the maximum strain rate $\dot{\epsilon}_{yA,max}$ appearing at the notch root over the average nominal strain rate at the minimum section $\dot{\epsilon}_{ynom}(t)$. It is found that the strain rate at the notch root $\dot{\epsilon}_{yA,max}$ depends on the dynamic stress rate at the notch root $\dot{\sigma}_{yA,max}$ and independent of the notch root radius ρ . It is found that the difference between the static and dynamic maximum stress concentration $(\sigma_{yA,max} - \sigma_{yA,st})$ at the notch root is proportional to the tensile speed when $u/t \leq 5000 \text{ mm/s}$. Strain rate concentration factors are also discussed with varying the notch depth and specimen length.

Key Words : *Stress Concentration; Notch; Dynamic Stress; Strain Rate; Finite Element Method ;*

Polycarbonate; Time-Temperature Superposition Principle

NOMENCLATURE

ρ : notch root radius in Fig.1

t : notch depth in Fig.1

d : width of minimum section in Fig.1

D : width of the specimen in Fig.1

L : specimen length

$u(t)$: displacement at the time in the y-direction at the fixed end

u_{\max} : maximum displacement at the fixed end

$\sigma_{yA}(t)$: dynamic stress at the notch root A at the time t

$\sigma_{yA,\max}$: maximum dynamic stress at the notch root A in Fig.5 and Fig.6

$\dot{\sigma}_{yA,\max}$: maximum dynamic stress rate at the notch root A in Fig.11

$\sigma_{ynom}(t)$: average dynamic stress at the minimum section

$\sigma_{yA,st}$: static stress at the notch root A

$\dot{\epsilon}_{yA}(t)$: strain rate at the notch root A at the time t

$\dot{\epsilon}_{yA,\max}$: maximum strain rate at the notch root A in Fig.8 and Fig.9

$\dot{\epsilon}_{ynom}(t)$: average strain rate at the minimum section

$K_{td}(t)$: dynamic stress concentration factor defined as $\sigma_{yA}(t)/\sigma_{ynom}(t)$

$K_{t\dot{\epsilon}}(t)$: dynamic strain rate concentration factor defined as $\dot{\epsilon}_{yA}(t)/\dot{\epsilon}_{ynom}(t)$

K_{t0} : stress concentration for the semi-infinite plate

$K_{t\dot{\epsilon}0}$: strain rate concentration for the limiting values $2t/D \rightarrow 0$

$\dot{\epsilon}_{yA,const}$: converged strain rate at the notch root A in Fig.8 and Fig.9

$\dot{\epsilon}_{ynom,const}$: converged average strain rate at minimum section in Fig.17

$\dot{\epsilon}_{const}^{smooth} = \frac{u/t}{L}$: converged strain rate of smooth specimen in Fig.18

INTRODUCTION

Engineering plastics are widely used in everyday products. Typically, an engineering plastic is chosen for its range of enhanced physical properties. For example, polycarbonate has superior impact resistance compared with other polymers, or indeed compared with some structural metals.¹ Most thermoplastics far below their glass transition give a brittle fracture when deformed in uniaxial tension. Polycarbonate is an exception and deforms in a ductile manner. However, Izod impact studies for notched specimens show that the mode of failure changes from ductile to a brittle fracture on annealing samples below T_g . Since the brittle-ductile transition is affected by temperature and loading speed,^{2,3} a high-speed tensile test is recently being recognized as a standard testing method. Bluntly notched specimens failed in a fully ductile manner, and sharply notched specimens failed in brittle manner depending on the strain rate at the notch root.

It should be noted that Izod and Charpy impact tests are not suitable for evaluating the impact strength of real products because the impact speeds do not correspond to the real failure. In the high-speed tensile test, it is necessary to obtain the strain rate correctly to understand the impact strength of the polymer specimen. For smooth specimens, the strain rate can be determined as $\dot{\epsilon}_{const}^{smooth} = u / tL$ from the specimen length L and the tensile speed u/t (see Fig.1 and Fig.4). On the other hand, for notched specimens, it is necessary to measure the strain at the notch root by strain gauge measurement, for example. However, since only the average value of the strain concerning the gauge width can be measured, it is not possible to measure the strain at the notch root accurately.

In the previous impact studies, circular holes⁴ and elliptical holes⁵ were investigated under step load^{6,7} and pulse load.^{7,8} In addition, review papers are also available for impact problems.⁹⁻¹¹ However, there are few studies on the strain rate concentration for notched specimens under various tensile speed. Therefore, in this paper, the finite element method is applied to analyze the notched specimens under various tensile speed. Then, the

dynamic stress concentration factor and the strain rate factor will be discussed with varying tensile speed and maximum values of forced displacement. In this study, to clarify the dynamic stress and strain rate behavior, the finite element elastic analysis is performed by using the software, FEM code MSC. Marc/Mentat 2005. In order to express dynamic stress oscillation, stiffness matrix multiplier coefficients are obtained by Fourier modal analysis and used in the elastic analysis.¹²

STATIC STRESS CONCENTRATION FOR DOUBLE-EDGE-NOTCHED SPECIMENS USED IN HIGH TENSILE LOAD

Fig. 1 + Fig.2

In this study, the material analyzed is assumed as polycarbonate, which has especially high impact strength among the polymeric materials. Young's modulus is assumed as $E = 2.3 \text{ GPa}$ with Poisson's ratio $\nu = 0.37$. Figure 1 shows the geometry of the double-edge-notched specimen, with dimensions of notch root radius $\rho = 0.03 \text{ mm}$ and 0.2 mm , notch depth $t = 5 \text{ mm}$, and opening angle 90° . The notch root radius $\rho = 0.03 \text{ mm}$ corresponds to the radius of fillet appearing at polymer products generally. The notch root radius $\rho = 0.2 \text{ mm}$ corresponds to the radius of the notched specimens used in the Izod and Charpy test. When the high-speed tensile test is performed, both ends of the specimen are gripped by rigid chuck, then forced displacement is applied to the end under constant speed. Figure 2 shows FEM models for analysis. Here Model 1 has the notch radius $\rho = 0.03 \text{ mm}$, and Model 2 has $\rho = 0.2 \text{ mm}$. Figure 2(c) shows the notch root detail in Model 1, and Fig. 2(d) shows the notch root detail in Model 2. Minimum mesh size of the notch root is $e = \rho/243$ each model. Figure 3 shows the boundary conditions given to the end portion of

the analysis models. Figure 3(a) shows boundary conditions in the rigid chucks, and Fig.3(b) shows a tensile stress boundary conditions generally used. Table 1 shows the effect of the difference in the boundary conditions on the static stress concentration factor. From Table 1, the stress concentration factor is almost the same in the tension by rigid chucks and the uniform tensile stress for the span length as shown in Fig.1. Also, Table 1, results using the model of Fig. 2, shows less than 1% error with respect to the exact stress concentration factor calculated by the approximate expression.¹³⁻¹⁷ Thus, Model 1, 2 are found to provide high accuracy. In the dynamic analysis, time step interval also affects the accuracy of the results. In this analysis, the time step 1×10^{-6} is found to be enough to obtain 3-digit-accuracy.¹⁸ In a transient dynamic analysis, damping represents the dissipation of energy in the structural system. In FEM code MSC. Marc/Mentat 2011 the program bases integration on the usual assumption that the damping matrix of the system is a linear combination of the mass and stiffness matrices. Element damping uses coefficients on the element matrices and is represented by the equation:

$$[C] = \alpha[M] + \beta[K] \quad (1)$$

Here $[C]$ is the global damping matrix, $[M]$ is the mass matrix and $[K]$ is the stiffness matrix. Because of the same damping coefficients are used throughout the structure, the following equation can be used to obtain the mass damping coefficient α and the usual stiffness damping coefficient β . The mass damping coefficient and the usual stiffness damping coefficient will be used for the dynamic analysis.

$$\zeta = \frac{1}{2} \left(\frac{\alpha}{\omega} + \beta \omega \right) \quad (2)$$

Here ζ is the damping ratio and ω is the frequency which can be calculated by FEM.

Fig. 3 + Table 1

DYNAMIC STRESS CONCENTRATION FOR HIGH SPEED TENSILE TEST SPECIMENS

Fig. 4

Figure 4 shows the forced displacement u given at the end of the specimen. The average stress σ_{gross} is also indicated, which is expressed as $\sigma_{gross}(t) = 0.867E \cdot u(t) / L$ from FEM analysis. The nominal stress at the minimum section is expressed as $\sigma_{net} = (D/d)\sigma_{gross}$. Here, we mainly consider 5 cases, as shown in Table 2. Table 2 shows the

Table 2

tensile speed, the maximum forced displacement of the fixed end and the time of that appear. In Case 5, the tensile speed $u/t = 5000mm/s$ corresponds to the impact speed when someone dropped a call phone to the ground. The maximum displacement $1.5mm$ correspond to the brittle fracture appearing at high speed tensile test. The maximum displacement $0.1mm$ corresponds to the case of nondestructive for high speed tensile test.

Fig. 5 + Fig. 6

Figure 5 and 6 show the dynamic stress at the notch root A for Cases 1-5. Also Fig. 5 and 6 show the detail of the dynamic stress oscillation with each case. From Fig. 4 and Fig. 5, it is seen that the maximum dynamic stress $\sigma_{yA,max}$ appears at almost the same time of the maximum forced displacement. Defined as the maximum value of dynamic stress $\sigma_{yA,max}$ in each case. After several oscillations due to the stress wave, dynamic stress approaches static stress $\sigma_{yA,st}$. From the comparison between Case 1 and Case 2, it is

shown that the maximum dynamic stress oscillation $(\sigma_{yA,\max} - \sigma_{yA,st})$ at the notch root point A in Case is larger than that in Case 1. From the comparison between Case 2 and Case 3, it is seen that of the same maximum dynamic stress oscillation $(\sigma_{yA,\max} - \sigma_{yA,st})$ at the notch root point A is observed although the final displacement of Case 3 is 15 times larger than that in Case 2. It is may be concluded that the maximum dynamic stress oscillation $(\sigma_{yA,\max} - \sigma_{yA,st})$ is controlled by the tensile speed. Figure 7 shows the relationship between

Fig. 7

the tensile speed u/t and $(\sigma_{yA,\max} - \sigma_{yA,st})$ for $\rho = 0.03mm$ and $0.2mm$. Here the results for $u/t = 100000, 1000000mm/s$ and step load $u/t = \infty$ are also indicated when the maximum displacement is $1.5mm$. It is seen that $(\sigma_{yA,\max} - \sigma_{yA,st})$ is proportional to the tensile speed when $u/t \leq 5000mm/s$. However, $(\sigma_{yA,\max} - \sigma_{yA,st})$ becomes constant when $u/t \geq 100000mm/s$. This is related to the fact that stress wave propagation speed is equal to the sonic wave propagation speed. Here, $u/t \geq 100000mm/s$ corresponds to the automobile crashing speeds.

STRAIN RATE CONCENTRATION FOR HIGH SPEED TENSILE TEST SPECIMEN

Fig. 8 + Fig. 9

Figure 8 and 9 show the strain rate at the notch root A for Cases 1-5 in Fig.4. The

strain rate increases dramatically at the start of applying forced displacement. Then, after several oscillations, the strain rate becomes constant. After stopping the forced displacement, several oscillations appear again, then it eventually converges to zero. From the comparison between Case 3 and Case 4, it is seen that the same maximum strain rate $\dot{\epsilon}_{yA,\max}$ and the same converged strain rate $\dot{\epsilon}_{yA,\text{const}}$ are observed although the final displacement u_{\max} of Case 3 is 15 times larger than that in Case 2. It may be concluded that the strain rate concentration is controlled by the tensile speed.

Fig. 10

Figure 10 shows the relationship between the tensile speed u/t and the strain rate for $\rho = 0.03\text{mm}$ and 0.2mm . Here the results for $u/t = 100000, 1000000\text{mm/s}$ and step load $u/t = \infty$ are also indicated when the maximum displacement is 1.5mm . It is seen that the strain rate is proportional to the tensile speed when $u/t \leq 5000\text{mm/s}$. However, the strain rate becomes constant when $u/t \geq 100000\text{mm/s}$.

Figure 10 shows that the maximum strain rate $\dot{\epsilon}_{yA,\max}$ is controlled by the tensile speed, that is the nominal strain rate at the fixed end. Next, we focus on the relationship at the notch root A. Figure 11 shows the relationship between the strain rate at the notch root and the dynamic stress rate at the notch root $\dot{\sigma}_{yA,\max}$ when the radius is 0.2mm and 0.03mm . The dynamic stress at the notch root is the value when the strain rate at the notch root becomes to be constant. As shown in Figure 11 it is found that the strain rate at the notch root is controlled by the dynamic stress rate at the notch root $\dot{\sigma}_{yA,\max}$ and independent of the notch root radius ρ . In this study, $\rho = 0.2$ and $\rho = 0.03$ are considered. However, the result to any notch root radius ρ can be predicted from Fig.11 if the dynamic stress rate at the notch root $\dot{\sigma}_{yA,\max}$ can be calculated.

Fig. 11

DYNAMIC STRESS DISTRIBUTION AT THE MINIMUM SECTION

Fig. 12

Figure 12 shows the dynamic stress distributions at the minimum section when the maximum dynamic stress appears. The dynamic stress concentration factor $K_{td}(t)$ is defined by the maximum dynamic stress $\sigma_{yA,max}$ at the notch root over the average dynamic stress $\sigma_{y,nom}(t)$ at the minimum section at each time. From Fig.12, when $\rho = 0.03mm$, it is seen that the maximum dynamic stress $\sigma_{yA,max}$ at the notch root is always 14.48 times larger than that of the nominal stress $\sigma_{y,nom}(t)$ at the minimum section at each time for Case 1 –Case 5. Similarly, when $\rho = 0.2mm$, the maximum dynamic stress $\sigma_{yA,max}$ at the notch root is always 6.43 times larger than that of the nominal stress $\sigma_{y,nom}(t)$ at the minimum section at each time for Case 1 –Case 5. The stress concentration factor coincides with the static stress concentration factor obtained by the formula of Murakami and Noda et al..¹³⁻¹⁷

Fig. 13

Figure 13(a) shows the maximum dynamic stress $\sigma_{yA,max}$ at the notch root and nominal dynamic stress $\sigma_{y,nom}(t)$. Figure 13(b) shows the dynamic stress factor $K_{td}(t)$. It is seen that $K_{td}(t)$ is constant although $\sigma_{yA,max}$ and $\sigma_{y,nom}(t)$ are changed depending on the time. This is because the maximum dynamic stress at the notch root and the nominal

dynamic stress are similarly controlled by the time. It may be concluded that the dynamic stress concentration factor is always constant and controlled by the notch shape alone. Therefore, from the results of the dynamic stress at the minimum section the maximum stress can be determined.

Fig. 14 + Table 3

Table 3 and Figure 14 show the dynamic stress concentration factor with varying $2t/D$. The limiting values for $2t/D \rightarrow 0$ correspond to the results for the semi-infinite plate. Figure 14(b) shows the ratio K_t/K_{t0} where K_{t0} is the results for semi-infinite plate.¹³⁻¹⁷ As show in Fig.14 (b) the results are independent of the notch root radius.

STRAIN RATE DISTRIBUTION AT THE MINIMUM SECTION

Fig. 15

Figure 15 shows the strain rate distributions at the minimum section when the maximum strain rate appears. The strain rate concentration factor $K_{t\dot{\epsilon}}(t)$ is defined by the maximum strain rate $\dot{\epsilon}_{yA,\max}$ at the notch root over the average strain rate $\dot{\epsilon}_{y,nom}(t)$ at the minimum section at each time. From Figure 15, when $\rho = 0.03mm$, it is seen that the maximum strain rate $\dot{\epsilon}_{yA,\max}$ at notch root is always 18.1 times larger than that of the nominal strain rate $\dot{\epsilon}_{y,nom}(t)$ at the minimum section for Case 1 –Case 5. Similarly, when $\rho = 0.2mm$ the maximum strain rate $\dot{\epsilon}_{yA,\max}$ at the notch root is always 8.72 times larger than that of the nominal strain rate $\dot{\epsilon}_{y,nom}(t)$ at the minimum section for Case 1 –Case 5.

Fig. 16

Figure 16(a) shows the strain rate at the notch root and nominal strain rate. Figure 16(b) shows the strain rate factor $K_{t\dot{\epsilon}}(t)$. It is seen that $K_{t\dot{\epsilon}}(t)$ is constant although $\dot{\epsilon}_{yA,\max}$ and $\dot{\epsilon}_{y,nom}(t)$ are changed depending on the time. It may be concluded that the strain rate concentration factor is always constant and controlled by the notch shape alone.

Table 4 + Fig. 17

Table 4 and Figure 17 show the strain rate concentration factor with varying $2t/D$. The limiting values $K_{t\dot{\epsilon}0}$ for $2t/D \rightarrow 0$ are obtained by the extrapolation from the results for $2t/D = 0.1, 0.25$. As shown in Fig.17 (b) the results are almost independent of the notch root radius.

EFFECT OF SPECIMEN LENGTH UPON THE DYNAMIC STRESS CONCENTRATION AND STRAIN RATE CONCENTRATION

Table 5

The effect of specimen length on the strain rate $\dot{\epsilon}_{const,nom}$ is considered. Table 5 shows the results for smooth specimen. It is seen that the strain rate $\dot{\epsilon}_{const}^{smooth} = \frac{u/t}{L}$ is independent of the width of specimen D . Here, $\dot{\epsilon}_{const,nom}$ is converged and average strain rate in Fig.15(a). Table 6 and Fig.18 show the average strain rate $\dot{\epsilon}_{const,nom}$ with varying $2t/D$ and specimen length L in comparison with the results for plane specimen $\dot{\epsilon}_{const}^{smooth}$.

Fig.18 indicate the ratio $\dot{\epsilon}_{const,nom} / \dot{\epsilon}_{const}^{smooth}$. As shown in Fig.19, with increasing $2t/D$, the ratio $\dot{\epsilon}_{const,nom} / \dot{\epsilon}_{const}^{smooth}$ increases. The average strain rate $\dot{\epsilon}_{const,nom}$ depends on the specimen length as shown in Fig.19. If the specimen length L is fixed, the average strain rate is independent of the notch root radius ρ as shown in Fig.15(a).

Table 6 + Fig. 18 + Fig. 19

APPLICATION OF THE TIME-TEMPERATURE SUPERPOSITION PRINCIPLE TO POLYCARBONATE

Depending on the test temperature and tensile speed, brittle or ductile fractures are observed for polycarbonate. Figure 20 shows the relationship between the nominal fracture strain and the notch root strain rate under various temperatures of polycarbonate, when $\rho = 0.2\text{mm}$ which is used in Izod and Charpy test. The high strain-rate or low temperature causes the brittle fracture. It is known that the time-temperature superposition can be frequently applied to determine the temperature dependence of the time or frequency at a given temperature of the polymeric material¹⁹. In this study therefore the impact properties are considered in terms of the time-temperature superposition principle. Here the shift factor a_T is obtained by the reference temperature $T_0 = 296\text{K}$ and the empirical constants $C_1 = 0.71$, $C_2 = 63.4$ ²⁰.

$$\log a_T = -\frac{C_1(T - T_0)}{C_2 + (T - T_0)} \quad (3)$$

Then, the master curve for the final fracture elongation for polycarbonate is obtained in terms of the strain rate at the notch in conjunction with shift factors. The fracture behavior can be predicted for the wide range of impact speed under various temperatures from the master curve. Based on the elastic strain concentration factor, the master curve is obtained

for the wide range as shown in Fig.21. It is found that the elastic analysis is useful and the strain rate at the notch is controlling the fracture behavior of polycarbonate.

Fig. 20 + Fig. 21

CONCLUSIONS

Recently, high-speed tensile test is being used as a standard testing method to evaluate impact strength of the engineering plastics and the other materials. For polymeric material, the strain rate and dynamic stress concentration is significant factors to be considered in the fracture. However, it is not easy to measure the dynamic stress or strain rate accurately at the notch root by experiment. In this study, therefore, dynamically and elastic FEM is applied to the high-speed tensile test for notched specimens. Then, the dynamic stress and strain rate concentrations have been discussed under various tensile speed. The conclusions can be made the following way.

(1) It may be concluded that the maximum strain rate increases with increasing the tensile speed as shown in Fig.10. However, the strain rate concentration factor $K_{t\dot{\epsilon}}(t) = \dot{\epsilon}_{yA}(t) / \dot{\epsilon}_{ynom}(t)$ is always constant. Here the $K_{t\dot{\epsilon}}$ which is defined by the maximum strain rate $\dot{\epsilon}_{yA,max}$ at the notch root over the average strain rate $\dot{\epsilon}_{ynom}(t)$ at the minimum section at each time.

(2) It may be concluded that the dynamic stress concentration factor $K_{td} = \sigma_{yA,max} / \sigma_{y,nom}(t)$ is always constant and controlled by the notch shape alone independent of the tensile speed. The stress concentration factor K_{td} coincides with the static stress concentration factor K_{ts} obtained as the formula in the references.¹³⁻¹⁷

- (3) It is found that the difference between the static and dynamic maximum stress concentration $(\sigma_{yA,\max} - \sigma_{yA,st})$ at the notch root increases in proportional to the tensile speed when $u/t \leq 5000 \text{ mm/s}$.
- (4) It is found that the strain rate at the notch root $\dot{\epsilon}_{yA,\max}$ depends on the quasi-static stress rate at the notch root $\dot{\sigma}_{yA,\max}$ alone and independent of the notch root radius ρ .
- (5) The master curve for the final fracture elongation for polycarbonate can be expressed in terms of the strain rate at the notch in conjunction with shift factors. The fracture behavior can be predicted for the wide range of impact speed under various temperatures from the master curve.

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TABLE HEADINGS

Table 1 Static stress concentration factor by FEM

Table 2 Displacement u given at the grip end

Table 3 Dynamic stress concentration factor K_{td} and the ratio K_{td}/K_{t0} (K_{t0} =the results for semi-infinite plate by Noda et al. (1995, 2002, 2010))

Table 4 Strain rate concentration factor $K_{t\dot{\epsilon}}$ and the ratio $K_{t\dot{\epsilon}}/K_{t\dot{\epsilon}0}$ (The limiting values $K_{t\dot{\epsilon}0}$ for $2t/D \rightarrow 0$ are obtained by the extrapolation from the results for $2t/D = 0.1$ and 0.25 .)

Table 5 Converged strain rate $\dot{\epsilon}_{const}^{smooth}$ for smooth specimen relation width of specimen .

Table 6 Converged average Strain rate $\dot{\epsilon}_{const,nom}$ for the notchd specimen.

FIGURE CAPTIONS

Fig.1 Geometry of specimen

Fig.2 FEM models ((a) Model 1 (b) Model 2 (c) Notch root detail in Model 1 (d) Notch root detail in Model 2)

Fig.3 Boundary conditions ((a)Grip tension (b)Simple tension)

Fig.4 Loading conditions defined as Case 1- Case 5 shown as ①-⑤ ((a) Displacement vs. time (b) Detail of displacement)

Fig.5 Dynamic stress at notch root A when $\rho = 0.03mm$ for (a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4 (e) Case 5 (f) All cases, Case 1- Case 5 as shown ①-⑤ in Fig.4

Fig.6 Dynamic stress at notch root A when $\rho = 0.2mm$ for (a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4 (e) Case 5 (f) All cases defined in Fig.4, Case 1- Case 5 as shown ①-⑤ in Fig.4

Fig.7 Difference between the static and dynamic maximum stress concentrations
 $(\sigma_{yA,max} - \sigma_{yA,st})$

Fig.8 Strain rate at notch root A when $\rho = 0.03mm$ for (a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4 (e) Case 5 defined in Fig.4, Case 1- Case 5 as shown ①-⑤ in Fig.4

Fig.9 Strain rate at notch root A when $\rho = 0.2mm$ for (a) Case 1 (b) Case 2 (c) Case 3 (d) Case 4 (e) Case 5 defined in Fig.4, Case 1- Case 5 as shown ①-⑤ in Fig.4

Fig.10 Maximum strain rate and converged strain rate vs. tensile speed for the notch root radios $\rho = 0.2mm$ and $\rho = 0.03mm$

Fig.11 Maximum strain rate $\dot{\epsilon}_{yA,max}$ and converged strain rate $\dot{\epsilon}_{yA,const}$ vs. quasi-static stress rate at the notch root $\dot{\sigma}_{yA,max}$ useful for all notch radius

Fig.12 Dynamic stress distribution along minimum section when the maximum dynamic

stress appears for $\rho = 0.2mm$ ((a)Case 2 (b)Case 3 (c)Case 5 defined in Fig.4)

Fig.13 Constancy of dynamic stress concentration factor

Fig.14 Dynamic stress concentration factor $K_{td}(t)$ vs. notch depth $2t/D$ relation

Fig. 15 Strain rate distribution along minimum section when the maximum strain rate appears for $\rho = 0.03mm$ ((a)Case 2 (b)Case 3 (c)Case 5)

Fig.16 Constancy of strain rate concentration factor

Fig.17 Strain rate concentration factor $K_{t\dot{\epsilon}}$ vs. notch depth $2t/D$ relation

Fig.18 Converged average strain rate $\dot{\epsilon}_{const,nom}$ vs. notch depth $2t/D$ relation

Fig.19 Ratio $\dot{\epsilon}_{const,nom} / \dot{\epsilon}_{const}^{smooth}$ vs. notch depth $2t/D$ relation

Fig. 20 Final fracture strain of polycarbonate obtained under various tensile speed and temperatures when $\rho = 0.2mm$

Fig.21 Master curves for final fracture strain \mathcal{E}_b of polycarbonate expressed in terms of reduced strain rate to predict ductile or brittle fracture ($\rho = 0.2mm$)

